

## Both age and physical activity level impact on eye-hand coordination



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### ABSTRACT

Aging impacts on our ability to perform goal-directed aiming movements. Older adults generally make slower and shorter initial impulses towards the end target, and therefore require more time for corrections in the final movement stage. Recent studies however suggest that a physically active lifestyle may attenuate these age-related changes. Also, it remains unclear whether eye-movement control exhibits a similar pattern of adaptation in older adults. Therefore, the first aim of this study was to describe how age and physical activity level impact eye-hand coordination during discrete manual aiming. Young and older participants were divided into physically active and sedentary subgroups, and performed discrete aiming movements while hand and eye movements were recorded. Secondly, to determine whether older adults depend more on vision during aiming, the task was repeated without visual feedback. The results revealed that the typical age-related hand movement adaptations were not only observed in older, but also in sedentary young participants. Older and sedentary young participants also spent more hand movement time after the eyes fixated the end target. This finding does not necessarily reflect an augmented reliance on vision, as all groups showed similar aiming errors when visual feedback was removed. In conclusion, both age and physical activity level clearly impacted eye-hand coordination during discrete manual aiming. This adapted coordination pattern seems to be caused by other factors than an increased reliance on vision.

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## 1. Introduction

According to the *multiple-process model of limb control* (Elliott et al., 2010) manual aiming movements such as pressing a light button or picking up a glass of wine consist of two consecutive phases: a primary submovement and a homing-in phase. The primary submovement corresponds to the initial pulse towards the vicinity of target. Although this pre-programmed movement phase is traditionally associated with open-loop control (Woodworth, 1899), recent work has shown that subtle movement trajectory corrections can already occur during the primary submovement (i.e., impulse control; see also Khan et al., 2006 and Saunders & Knill, 2003). Still, the main body of closed-loop control occurs during the homing-in phase: here, proprioceptive and visual feedback is used to correct for any spatial discrepancy between hand and target positions (i.e., limb-target control). Previous research has shown that primary submovements generally undershoot the target to allow corrections in the same direction as the initial pulse (Elliott, Helsen, & Chua, 2001; Engelbrecht, Berthier, & O'Sullivan, 2003; Heath, 2005; Helsen, Elliott, Starkes, & Ricker, 1998). This type of correction entails lower energy-costs than correcting for target overshoots, as reversals involve overcoming the inertia of a zero-velocity situation and the limb traveling a greater total distance (Elliott, Hansen, Mendoza, & Tremblay, 2004; Elliott et al., 2010; Welsh, Higgins, & Elliott, 2007).

Interestingly, by slowing down their primary submovement, older adults tend to undershoot the target to an even greater extent than young controls (Ketcham, Seidler, Van Gemmert, & Stelmach, 2002; Poston, Van Gemmert, Barduson, & Stelmach, 2009; Pratt, Chasteen, & Abrams, 1994). As a result, they travel a larger distance in the homing-in phase and consequently need more time to complete feedback-based adjustments (Boisseau, Scherzer, & Cohen, 2002; Ketcham et al., 2002; Lyons, Elliott, Swanson, & Chua, 1996). This results in overall greater movement times. Older adults thus spend relatively more time on the homing-in phase, suggesting an increased reliance on limb-target control (Coats & Wann, 2011; Seidler-Dobrin & Stelmach, 1998).

Though the majority of studies consistently found the abovementioned age-related changes, there are some exceptions. For instance, Lyons et al. (1996) reported no differences between young and older adults' movement times, accuracy levels, and primary submovement trajectories. To explain these unexpected results, the possible influence of a physically active lifestyle was raised. Recently, our lab found support for this statement: When comparing manual aiming kinematics of physically active and sedentary older adults, the typical age-related movement adaptations were observed only in sedentary older adults, but not in physically active ones (Van Halewyck, Lavrysen, Levin, Elliott, & Helsen, *in press*). Though this study focused mainly on cyclical aiming, its outcome suggests that a physically active lifestyle might counteract the mechanism(s) underlying the age-related alterations of aiming movements. More specifically, high levels of physical activity have already shown to attenuate age effects playing a key role in manual aiming such as sarcopenia (DiPietro, 2001) and the gradual decline in proprioceptive acuity (Wright, Adamo, & Brown, 2011). The level of physical activity should therefore be considered as a possible mediating factor when studying manual aiming in older participants.

Given the role visual feedback plays in limb regulation, it is surprising that most investigators have neglected to examine eye movements. Ocular motor literature has shown that the neuromuscular system underlying eye movements is only slightly affected or even spared by the aging process (Kadota & Gomi, 2010; Pratt, Dodd, & Welsh, 2006; Yang & Kapoula, 2006), as evidenced by equal movement times, movement speeds and saccadic amplitudes during volitional saccades among young and older adults (Pratt et al., 2006). However, recent work suggests older adults' eye-movement control might be compromised during manual aiming: Similar to the hand, older adults tend to make hypometric primary saccades followed by more corrective eye movements during two-segment aiming movements (Rand & Stelmach, 2011b; Rand & Stelmach, 2012). Remarkably, whether older adults' eye-movement control is also modified during one-segment aiming movements has not been studied to date.

Taken together, it remains unclear how both age and physical activity level impact on eye-hand coordination during discrete (one-segment) aiming movements. To address this question, young and older participants were divided in an active and sedentary subsample. Participants were asked to hit a small target as quickly and accurately as possible with a cursor controlled by wrist movements

(discrete single-joint aiming). Hand- and eye-movement kinematics and coordination were compared between the four groups. In line with the suggestion of Lyons et al. (1996) and our results in cyclical aiming (Van Halewyck et al., in press), a physically active lifestyle was expected to reduce the traditional age differences in discrete manual aiming. Also, based on the findings in two-segment aiming (Rand & Stelmach, 2011b; Rand & Stelmach, 2012) saccadic behavior was expected to adapt to the hand movement in all groups. This would, for instance, be reflected by relatively small primary sub-movements being accompanied by relatively small primary saccades.

The second aim of the study was to determine whether older adults indeed rely more on limb-target control during the execution of manual aiming movements. As limb-target control is based on both proprioceptive and visual feedback of the hand position, it should be underlined that proprioceptive acuity generally deteriorates with age (Wright et al., 2011), especially in challenging conditions (Boisgontier, Olivier, Chenu, & Nougier, 2012). Several investigators have suggested that visual feedback becomes increasingly important during older adults' aiming movements (Coats & Wann, 2011; Rand & Stelmach, 2011a; Terrier et al., 2011; Yan, Thomas, & Stelmach, 1998). To investigate this specific issue, the previously described task was also executed without visual feedback of the cursor. Consistent with the theory of an increased reliance on vision, the withdrawal of visual feedback was hypothesized to affect the aiming accuracy of older adults more than in the young.

## 2. Methods

### 2.1. Participants

Twenty-two young and 24 older adults participated in the study on a voluntary basis. All participants had normal or corrected-to-normal vision, and were right-handed as they scored 50 or more on the Edinburgh Handedness Inventory (Oldfield, 1971). Older adults nevertheless reported a slightly greater right hand preference than young adults (see Table 1 for general characteristics of all groups). Fine motor skills were considered intact, as all participants met the age- and gender-dependent criteria for the Nine Hole Pegboard Test (NHPT; Mathiowetz, Volland, Kashman, & Weber, 1985; Oxford Grice et al., 2003). To rule out participants with dementia or other anomalies in cognitive functioning, a Mini-Mental State Examination (MMSE) was administered to the older adults. The minimum score for inclusion was set at 28 out of 30, which all achieved. Within both age groups, participants were subdivided based on their physical activity level in daily life as assessed by the Baecke questionnaire (Baecke, Burema, & Frijters, 1982; Voorrips, Ravelli, Dongelmans, Deurenberg, & Van Staveren, 1991). Participants scoring higher than the median Baecke score (respectively 8.1 and 8.4 for young and older adults) were considered physically active, whereas participants scoring lower than the median score were considered sedentary. This subdivision resulted in four groups: physically active young adults

**Table 1**  
Participant Characteristics.

Characteristic	Young		Old		Significant effect?
	ACT	SED	ACT	SED	
<i>n</i>	11	11	12	12	/
Male/female	6/5	6/5	5/7	4/8	/
Age (in years)	22.9 ± 0.5	22.0 ± 0.6	65.1 ± 0.9	65.3 ± 1.1	AGE
Baecke score	9.7 ± 0.3	6.7 ± 0.3	9.3 ± 0.2	6.9 ± 0.3	PAL
Oldfield score	79.0 ± 4.6	74.0 ± 5.0	90.3 ± 4.1	89.6 ± 3.4	AGE
NHPT	16.0 ± 0.4	16.4 ± 0.6	19.9 ± 0.6	19.0 ± 0.8	AGE
MMSE score	/	/	29.0 ± 0.3	29.6 ± 0.2	/

*Note:* Results are presented as *mean ± SEM* when appropriate. Since these data could not be considered parametric, a Mann-Whitney *U* test was performed to calculate group differences. High Baecke scores indicate a physically active lifestyle, low Baecke scores a sedentary one; Oldfield scores indicate handedness (−100: extremely left-handed, +100: extremely right-handed). *Abbreviations:* NHPT = Nine Hole Pegboard Test; MMSE = Mini Mental State Examination; ACT = active subsample; SED = sedentary subsample; PAL = physical activity level.

( $n = 11$ , mean  $\pm$  standard error of the mean [SEM] Baecke score:  $9.7 \pm 0.3$ ), sedentary young adults ( $n = 11$ , Baecke score:  $6.7 \pm 0.3$ ), physically active older adults ( $n = 12$ , Baecke score:  $9.3 \pm 0.2$ ) and sedentary older adults ( $n = 12$ , Baecke score:  $6.9 \pm 0.3$ ). The study was approved by the Medical Ethics Committee of the KU Leuven and was conducted in accordance with the 1964 Declaration of Helsinki. Written informed consent was obtained from all participants prior to the experiment.

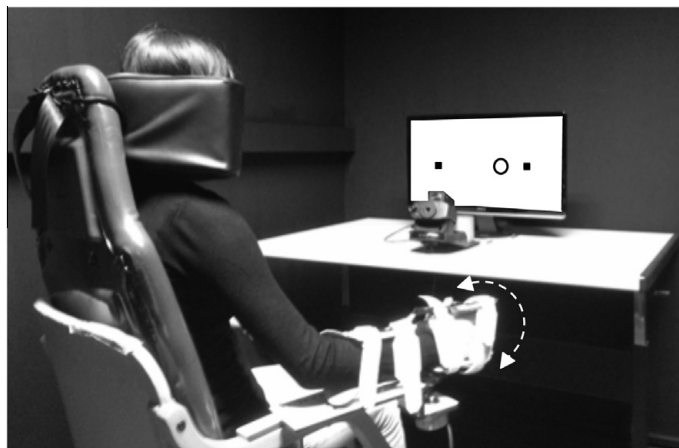
## 2.2. Apparatus

The apparatus was identical to the one used in several previous studies (e.g., Lavrysen, Elliott, Buekers, Feys, & Helsen, 2007; Lavrysen et al., 2008; Lavrysen et al., 2012; Van Halewyck et al., *in press*). As shown in Fig. 1, participants sat in a comfortable chair and wore an orthosis on the preferred, right forearm. The axis of the orthosis was aligned with the anatomical axis of the wrist joint and positioned in a way that the hand could only move in the horizontal plane. A high-precision shaft encoder with an accuracy of  $0.006^\circ$  and sampling frequency of 250 Hz was attached onto the orthosis. Wrist angular position was presented as a 1.5 cm diameter circular cursor on a 60 cm computer monitor, which was located at a standardized distance of 125 cm in front of the participant at eye level. Apart from this cursor, two fixed, square targets also appeared on the monitor. These targets had a width of 1 cm and stood 18 cm apart. In short, the task consisted of moving the cursor as fast and accurate as possible from the right to the left target by making  $15^\circ$  wrist flexion movements after the onset of a visual cue. As the target had to be entirely surrounded by the small cursor, the aiming movement had an index of difficulty (ID) of 6.2 bits ( $ID = \log_2[2 \cdot 18 / (1.5 - 1)]$ ). Wrist movements are commonly used to study manual aiming because they have been shown to obey *Fitts' Law* (Meyer, Abrams, Kornblum, Wright, & Smith, 1988) and they are relatively unaffected by mechanical factors that could mask active control processes (Khan & Franks, 2000). Exact instructions and different conditions are further explained in the *Task and Protocol* section.

Point of gaze (PG) was recorded using an Applied Science Laboratories (ASL) 6000 pan-tilt eye-tracker system (Bedford, MA) with an accuracy of  $0.5^\circ$ . Prior to the experiment, a nine-point calibration was performed for every participant. During each aiming movement horizontal PG coordinates were sampled at 240 Hz.

## 2.3. Task and protocol

The experiment started with an extensive familiarization phase during which the aiming task was practiced. When a block of aiming movements started, participants were instructed to place the cursor



**Fig. 1.** Test set-up. Participants placed their right forearm into an orthosis while seated in front of a computer screen showing two fixed square targets and a round cursor. Wrist flexion and extension movements moved a cursor towards the left or right of the screen, respectively. Participants were asked to move the cursor from the right to the left target as soon as the right (starting) target turned red. This trajectory corresponded to a  $15^\circ$  wrist flexion movement. Eye movements were recorded concurrently using an Applied Science Laboratories (ASL) 6000 pan-tilt eye-tracker system that was positioned in front of the computer screen.

around the right (black) target. In order to prevent anticipatory saccades, participants were asked repeatedly to fixate this starting position. As soon as the starting target turned red (GO-stimulus), they were to aim as fast and accurately as possible towards the left target (ID = 6.2 bits), corresponding to a 15° wrist flexion movement. Once the left target was entirely surrounded by the cursor, participants were asked to briefly close their eyes and head back to the right target to prepare for the next GO-stimulus. This sequence was repeated ten times per block. The interval between two consecutive GO-stimuli varied randomly between 6000, 6500, 7000, 7500 and 8000 ms to avoid movement anticipation.

During the familiarization period, participants first performed three practice blocks with online visual feedback of the cursor (VISION). Afterwards, the condition without visual feedback of the cursor (NO VISION) was practiced: Participants were instructed to make the same aiming movement, yet they were warned the cursor would disappear as soon as it left the starting target. In order to give the participants knowledge of results, the cursor reappeared after 2500 ms, a period long enough for all participants to complete the movement without visual feedback. Afterwards, participants were instructed to head back immediately towards the starting position and wait for the next GO-stimulus. Again, the block ended after ten aiming movements.

After three VISION and three NO VISION practice blocks, participants started the main experiment. It consisted of five blocks of ten movements per visual condition, resulting in 100 aiming movements per participant. In contrast to the familiarization phase, the order of the visual conditions was counterbalanced in the main experiment. To prevent participants from memorizing the final end position over blocks, the angular starting (and thus end) position of the wrist was regularly altered between blocks. More specifically, the angular position of the wrist that corresponded to the cursor standing on the starting target was slightly altered (some degrees more towards flexion or extension of the wrist) before starting the fourth practice block, and the first and sixth experimental blocks. As the amplitude of the requested wrist movement remained constant throughout the experiment, switching the starting position of the movement also changed the desired final position.

## 2.4. Dependent variables

Prior to the calculation of the dependent variables, a first order low-pass Butterworth filter with a cut-off frequency of 20 Hz was applied on both the hand- and eye-movement data (Lavrysen et al., 2007; Lavrysen et al., 2008; Lavrysen et al., 2012; Van Halewyck et al., *in press*). The filtered data were differentiated twice to obtain instantaneous velocity and acceleration profiles for hand and eye movements. As both effectors were recorded at different sampling frequencies, data were then interpolated in Matlab to get an accurate view on the temporal coupling between hand and eye movements.

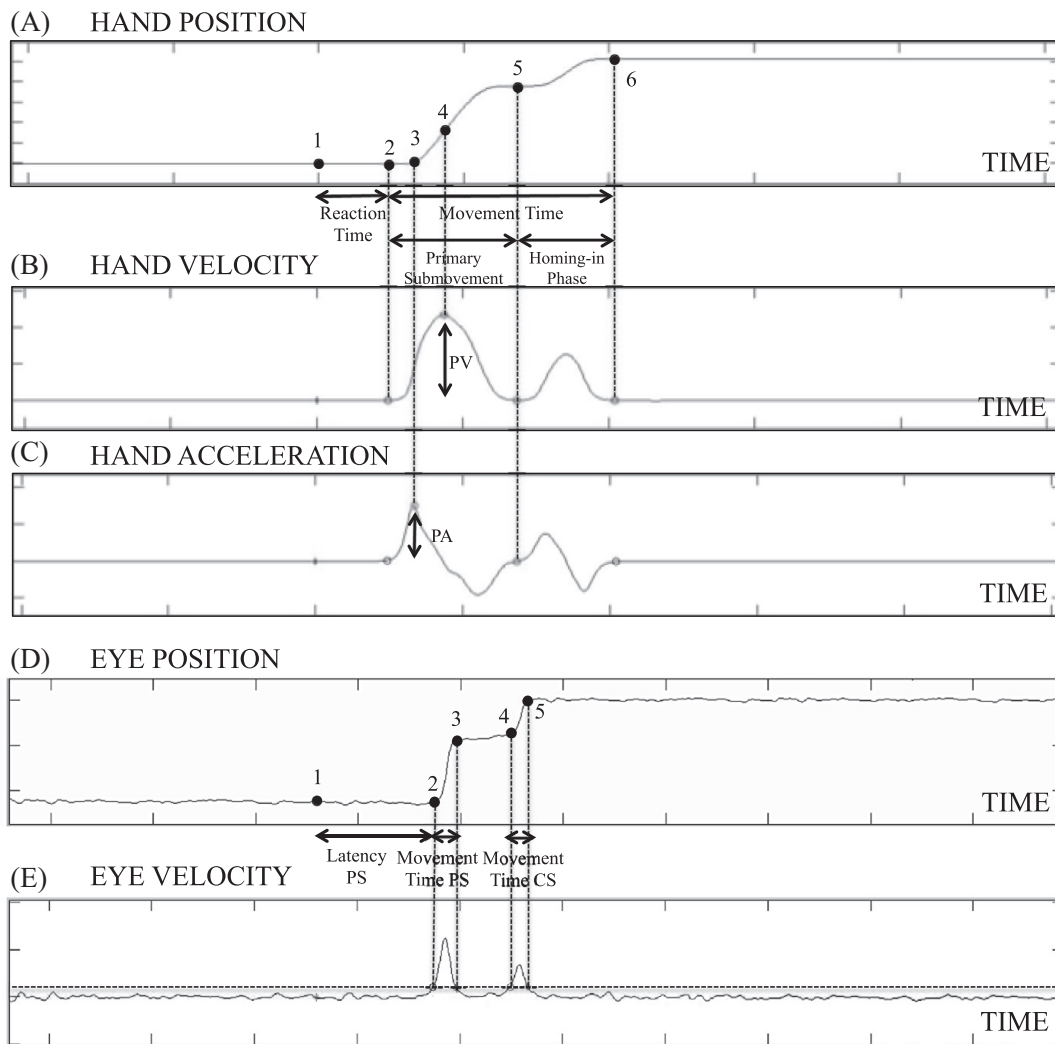
### 2.4.1. Hand kinematic markers

A schematic overview of all hand kinematic markers is given in Fig. 2A. First, the highest values in the acceleration and velocity profiles were respectively considered peak acceleration (PA) and peak velocity (PV). Then, hand movement initiation and termination were defined as the first sample when the standard deviation of the hand velocity profile was inferior to 0.75 mm/s for 80 ms from peak velocity backwards and onwards, respectively (Van Halewyck et al., *in press*). Finally, the end of the primary submovement was calculated using the criterion of Khan, Franks, and Goodman (1998). To gain better insight in the temporal trajectory of the hand movement, the exact duration to reach PA, PV and the end of the primary submovement was calculated relative to the overall movement time. Spatially, the exact positions of all five kinematic markers were also calculated relative to the distance between the start and end target (e.g., if the end of the primary submovement was reached when the cursor was exactly halfway the targets, this would yield a value of 50.0%).

### 2.4.2. Number of hand corrections

To get a better understanding of the homing-in phase of the movement, the number of hand corrections in the final movement stage was calculated. This variable was defined as the number of acceleration and deceleration pairs (two zero crossings) in the filtered acceleration profile between the end of the primary submovement and the hand movement termination (Ketcham et al., 2002).





**Fig. 2.** Schematic overview of the dependent variables. Examples of a typical hand position (A), hand velocity (B) and hand acceleration (C) profile are displayed on top. The following kinematic markers are displayed in Fig. 2A: (1) onset of the GO-stimulus, (2) hand movement initiation, (3) the moment of peak acceleration, (4) the moment of peak velocity, (5) the end of the primary submovement, and (6) hand movement termination. Reaction time of the hand was considered the difference between the onset of the GO-stimulus and hand movement initiation. Movement time was seen as the difference between hand movement initiation and termination. Defining the end of the primary submovement allowed us to divide the movement time into a primary submovement and homing-in phase. The lower graphs display examples of eye position (D) and eye velocity (E) profiles. The following kinematic markers are displayed in Fig. 2D: (1) onset of the GO-stimulus, primary saccade (2) initiation and (3) termination, and corrective saccades (4) initiation and (5) termination. The time between the onset of the GO-stimulus and the primary saccade initiation was considered the latency of the primary saccade. Identically to the hand, the movement time of the primary and corrective saccades were determined by the time between their initiation and termination.

#### 2.4.3. Endpoint accuracy

Regarding endpoint accuracy, an aiming movement was considered a target hit if the left target was completely surrounded by the cursor at the moment of hand movement termination. If the cursor fell short or long, it was defined as a target undershoot or overshoot, respectively. Finally, the exact unsigned distance between the middle of the cursor and the middle of the left target was calculated for each aiming movement. This value represented the aiming error of the movement.

#### 2.4.4. Eye kinematic markers

Parallel to the hand, a schematic overview of all eye kinematic markers is given in Fig. 2D. The primary saccade initiation was defined as the first sample after the GO-stimulus with the velocity profile

of the eye superior to  $30^\circ/\text{s}$  for at least 50 ms (Pratt et al., 2006). The final sample after the primary saccade initiation with the velocity profile of the eye still superior to this threshold was considered the primary saccade termination. After a subsequent fixation of minimally 50 ms in which the  $30^\circ/\text{s}$  threshold was not exceeded, an identical criterion was used to determine whether corrective saccades occurred. The latency of the primary saccade was defined as the time between the onset of the GO-stimulus and the primary saccade initiation. Primary and corrective saccades duration corresponded to the time between their initiation and termination. In order to get a better understanding of the eye–hand coordination, the timing of these kinematic markers was calculated relative to the hand movement time for each aiming movement. Furthermore, the amplitude of the primary and corrective saccades was calculated as the difference in horizontal PG coordinates between their initiation and termination. To simplify the interpretation of these variables, they are reported as a percentage of the distance between the targets.

#### 2.4.5. Number of eye corrections

The number of corrective saccades was calculated by counting how often the velocity profile of the eyes remained superior to  $30^\circ/\text{s}$  for at least 50 ms followed by a fixation (velocity profile of the eyes remained inferior to  $30^\circ/\text{s}$  for at least 50 ms) between the end of the primary saccade and the hand movement termination (Pratt et al., 2006).

#### 2.5. Data analysis

A custom-written Matlab script was used to compute the means and standard deviations of all abovementioned variables per block. First, two-way analyses of variance (ANOVA [AGE  $\times$  PHYSICAL ACTIVITY LEVEL]) were performed on the VISION condition data (see Table 2) and on the NO VISION condition data (see Table 3) separately. As saccades were only considered meaningful in the VISION condition, eye-movement data were excluded in the NO VISION condition analysis. Finally, the focus was shifted towards the importance of visual feedback during manual aiming by comparing the VISION condition hand data to the NO VISION condition hand data (see Table 4). This was done by performing a three-way ANOVA (AGE  $\times$  PHYSICAL ACTIVITY LEVEL  $\times$  VISUAL CONDITION) on all hand data. The significance level for all analyses was set at  $p < .05$ . Post-hoc tests (Tukey's honestly significant differences) were conducted when appropriate.

### 3. Results and discussion

In line with our research questions, the results are presented in two separate sections. First, the impact of age and physical activity level on hand- and eye-movement kinematics and coordination in the VISION condition is discussed. An overview of all group scores and effects is provided in Table 2. Second, the importance of visual feedback during discrete aiming, as can be derived from Tables 3 and 4, is briefly addressed. Bearing in mind the focus of the current study, only a selection of results is discussed in detail.

#### 3.1. Research question 1: What is the impact of age and physical activity level on eye–hand coordination during discrete manual aiming?

##### 3.1.1. Impact of age

Consistent with previous studies, hand reaction (Kadota & Gomi, 2010; Porciatti, Fiorentini, Morrone, & Burr, 1999; Poston et al., 2009) and movement (Coats & Wann, 2011; Rey-Robert, Temprado, Lemaire, & Berton, 2012; Temprado et al., 2013) times increased with age (both  $p < .0001$ ). Older adults' aiming movements were also less forceful and slower as can be derived from the lower PA and PV values (both  $p < .05$ ). In line with the literature, this resulted in primary submovements undershooting the target to a greater extent compared to young adults ( $p < .0001$ ; Ketcham et al., 2002; Poston et al., 2009; Pratt et al., 1994). Related to this substantial undershoot, the relative proportion of time older adults spent on the primary submovement was also lower ( $p < .0001$ ). In

**Table 2**  
First analysis: Hand- and eye-movement variables for all groups in the VISION condition.

Effector	Characteristic	Variable	Unit	Group score				F-value		
				Young		Old		AGE	PAL	AGE × PAL
				ACT (n = 11)	SED (n = 11)	ACT (n = 12)	SED (n = 12)			
Hand	Timing	Reaction time	Milliseconds	336 ± 22	341 ± 20	407 ± 26	383 ± 25	26.31***	0.74	1.64
		Movement time	Milliseconds	892 ± 62	1012 ± 66	1073 ± 65	1083 ± 67	25.91***	6.86***	4.85*
		%TTPA	% of movement time	8.6 ± 0.7	8.3 ± 0.7	8.1 ± 0.8	7.8 ± 0.7	5.04*	1.76	0.02
		%TTPV	% of movement time	20.5 ± 2.0	21.1 ± 2.2	20.0 ± 1.8	20.6 ± 1.9	0.62	0.80	0.00
	Position	%TTEnd Prim. Subm.	% of movement time	37.0 ± 3.6	35.3 ± 3.3	32.0 ± 3.1	32.2 ± 3.2	16.50***	0.54	0.90
		Start	% of target distance	−0.2 ± 0.1	−0.2 ± 0.1	−0.1 ± 0.1	−0.2 ± 0.1	5.62*	4.04*	2.21
		PA	% of target distance	1.7 ± 0.1	1.7 ± 0.3	1.7 ± 0.3	1.4 ± 0.1	1.33	3.10	3.00
		PV	% of target distance	35.7 ± 2.8	33.1 ± 3.4	32.8 ± 3.1	33.1 ± 2.9	2.71	1.85	2.76
	Accuracy	End Prim. Subm.	% of target distance	72.5 ± 4.1	64.4 ± 4.5	61.0 ± 4.4	60.2 ± 4.1	25.12***	8.04***	5.38*
		End	% of target distance	99.6 ± 0.4	99.7 ± 0.4	99.1 ± 0.4	99.0 ± 0.4	66.63***	0.45	3.62
Eyes	Accuracy	Target hit	% of trials	91.1 ± 3.5	89.5 ± 4.6	85.4 ± 3.7	83.6 ± 4.8	9.48***	0.79	0.01
		Target undershoot	% of trials	4.1 ± 2.0	3.3 ± 1.6	7.7 ± 2.7	11.4 ± 3.8	22.04***	1.30	3.29
		Target overshoot	% of trials	4.8 ± 0.8	7.2 ± 0.6	6.9 ± 0.5	5.0 ± 2.3	0.71	0.08	0.17
		Aiming error	% of target distance	0.9 ± 0.3	0.9 ± 0.3	1.2 ± 0.3	1.3 ± 0.3	24.78***	0.63	0.22
	Other	Value PA	cm/s <sup>2</sup>	1417 ± 81	1068 ± 70	1023 ± 60	1091 ± 82	5.55*	3.17	7.01***
		Value PV	cm/s	83.9 ± 4.3	64.1 ± 3.6	65.9 ± 3.1	65.3 ± 3.6	5.82*	8.68***	7.70***
	Timing	Number of corrections		2.27 ± 0.31	2.49 ± 0.31	2.75 ± 0.33	2.61 ± 0.33	10.43***	0.18	3.74
		Latency PS	Milliseconds	443 ± 30	509 ± 31	512 ± 35	470 ± 28	1.26	0.84	15.17***
	Position	Duration PS	Milliseconds	85 ± 5	78 ± 7	81 ± 6	85 ± 5	1.60	0.54	11.34***
		Amplitude PS	% of target distance	87.7 ± 3.8	81.5 ± 4.9	81.5 ± 3.5	86.1 ± 2.8	0.12	0.12	5.93*
Coordination	Other	Amplitude CS	% of target distance	13.9 ± 0.4	18.5 ± 0.6	18.5 ± 0.5	12.6 ± 0.4	0.08	0.07	5.34*
		Number of corrective saccades		0.72 ± 0.21	1.13 ± 0.21	1.06 ± 0.19	1.05 ± 0.18	1.14	3.03	3.35
	Timing	Start PS	% movement time (hand)	12.0 ± 4.5	16.6 ± 4.4	9.7 ± 4.4	8.0 ± 3.7	15.19***	1.13	4.95*
		End PS	% movement time (hand)	21.5 ± 3.0	24.3 ± 3.0	17.3 ± 2.6	15.8 ± 2.1	36.13***	0.39	4.03*
		Start CS	% movement time (hand)	44.3 ± 4.1	33.6 ± 4.1	25.4 ± 3.6	25.8 ± 3.2	76.91***	11.55***	13.04***
		End CS	% movement time (hand)	78.5 ± 4.5	63.0 ± 4.8	61.8 ± 4.0	55.9 ± 3.9	25.22***	20.25***	4.14*

Note: Group scores are presented as mean ± SEM, significant F-values are highlighted by \* (if  $p < .05$ ) or \*\*\* (if  $p < .01$ ). Abbreviations: %TTPA = relative time to peak acceleration; %TTPV = relative time to peak velocity; %TTEnd Prim. Subm. = relative time to end primary submovement; PV = peak velocity; End Prim. Subm. = end primary submovement; PS = primary saccade; CS = corrective saccades; ACT = active subsample; SED = sedentary subsample; PAL = physical activity level.



**Table 3**  
Second analysis: Hand-movement variables for all groups in the NO VISION condition.

Effector	Characteristic	Variable	Unit	Group score				F-value	
				Young		Old		AGE	AGE × PAL
				ACT (n = 11)	SED (n = 11)	ACT (n = 12)	SED (n = 12)		
Hand	Timing	Reaction time	Milliseconds	380 ± 24	392 ± 26	425 ± 38	430 ± 32	12.42***	0.52
		Movement time	Milliseconds	1104 ± 66	1184 ± 61	1301 ± 73	1280 ± 69	9.16***	0.37
	Position	%TTPA	% of movement time	8.8 ± 0.9	9.6 ± 0.9	7.6 ± 0.7	7.3 ± 0.7	21.25***	0.51
		%TTPV	% of movement time	25.2 ± 2.9	26.8 ± 3.6	21.5 ± 2.5	20.0 ± 2.4	32.60***	0.29
		%TTEnd Prim. Subm.	% of movement time	38.4 ± 3.9	36.7 ± 4.2	30.9 ± 3.2	30.4 ± 3.2	19.29***	0.54
	Position	Start	% of target distance	−0.2 ± 0.1	−0.3 ± 0.1	−0.2 ± 0.1	−0.2 ± 0.1	3.33	5.36*
		PA	% of target distance	1.8 ± 0.4	1.9 ± 0.6	1.4 ± 0.2	1.4 ± 0.2	17.92***	0.30
	Accuracy	PV	% of target distance	36.1 ± 3.8	34.4 ± 5.1	31.5 ± 3.7	29.1 ± 3.5	15.83***	2.73
		End Prim. Subm.	% of target distance	58.7 ± 4.5	54.9 ± 5.5	52.5 ± 4.9	50.8 ± 4.5	5.05*	1.45
		End	% of target distance	99.8 ± 2.9	98.3 ± 2.7	98.9 ± 2.4	97.7 ± 2.4	1.77	5.91*
	Accuracy	Target hit	% of trials	22.8 ± 5.0	22.6 ± 4.7	19.3 ± 4.3	23.0 ± 3.8	0.52	0.69
		Target undershoot	% of trials	37.4 ± 6.2	40.7 ± 4.4	39.0 ± 4.0	42.1 ± 4.8	0.45	1.99
	Other	Target overshoot	% of trials	39.8 ± 6.0	36.7 ± 4.4	41.7 ± 5.8	34.9 ± 5.4	0.10	2.43
		Aiming error	% of target distance	8.2 ± 1.8	7.4 ± 1.7	7.2 ± 1.4	7.3 ± 1.5	2.25	0.98
	Other	Value PA	cm/s <sup>2</sup>	762 ± 37	678 ± 31	776 ± 31	734 ± 29	0.60	1.99
	Other	Value PV	cm/s	50.8 ± 3.2	45.2 ± 2.7	50.5 ± 2.8	46.8 ± 2.4	0.05	2.67
		Number of corrections		2.39 ± 0.28	2.66 ± 0.32	3.35 ± 0.34	3.24 ± 0.34	19.78***	0.22

Note: Group scores are presented as mean ± SEM, significant F-values are highlighted by \* (if  $p < .05$ ) or \*\*\* (if  $p < .01$ ). Abbreviations: %TTPA = relative time to peak acceleration; %TTPV = relative time to peak velocity; %TTEnd Prim. Subm. = relative time to end primary submovement; PV = peak velocity; End Prim. Subm. = end primary submovement; ACT = active subsample; SED = sedentary subsample; PAL = physical activity level.

**Table 4**  
Third analysis: Impact of visual condition on hand variables.

Effector	Characteristic	Variable	Unit	F-value			
				VIS. CONDITION	AGE × VIS. CONDITION	PAL × VIS. CONDITION	AGE × PAL × VIS. CONDITION
Hand	Timing	Reaction Time	Milliseconds	21.87***	1.00	1.24	0.48
		Movement Time	Milliseconds	55.53***	0.14	0.44	0.01
		%TTPA	% of movement time	0.03	8.61***	1.67	1.26
		%TTPV	% of movement time	14.68***	19.06***	0.00	0.74
Position	End Prim. Subm.	%TTEnd Prim. Subm.	% of movement time	0.02	2.37	0.05	0.04
		Start	% of target distance	2.35	0.12	0.06	1.46
		PA	% of target distance	0.09	7.21***	2.27	0.13
		PV	% of target distance	1.67	5.43*	0.33	1.44
		End Prim. Subm.	% of target distance	53.05***	0.99	0.38	0.90
		End	% of target distance	5.62*	0.03	5.60*	0.26
Accuracy	Target hit	Target hit	% of trials	1841.10***	2.39	1.48	0.53
		Target undershoot	% of trials	643.58***	2.80	0.49	0.83
		Target overshoot	% of trials	806.91***	0.17	2.42	0.13
		Aiming error	% of target distance	1101.05***	5.86*	1.29	0.91
Other	Value PA	Value PA	cm/s <sup>2</sup>	79.02***	5.76*	0.70	4.17*
		Value PV	cm/s	89.88***	3.97*	1.49	3.66
		Number of corrections		15.68***	6.05*	0.05	0.01

Note: Significant F-values are highlighted by \* (if  $p < .05$ ) or \*\*\* (if  $p < .01$ ). Abbreviations: %TTPA = relative time to peak acceleration; %TTPV = relative time to peak velocity; %TTEnd Prim. Subm. = relative time to end primary submovement; PV = peak velocity; End Prim. Subm. = end primary submovement; VIS. CONDITION = visual condition; PAL = physical activity level.

other words, older adults spent a larger relative (and absolute) amount of time homing-in on the target (Boisseau et al., 2002; Pratt et al., 1994; Welsh et al., 2007), an outcome that may be directly associated with their higher number of hand trajectory corrections ( $p < .005$ ; Boisseau et al., 2002; Ketcham et al., 2002; Lyons et al., 1996). Interestingly, despite these movement adaptations older adults achieved lower accuracy levels than young adults as can be derived from the percentage of target hits ( $p < .005$ ; see Fig. 3A). This notion is additionally supported by older adults' greater aiming errors ( $p < .0001$ ), indicating they usually ended their movement further away from the middle of the target than young adults.

In contrast to the hand, all eye kinematic markers were similar in young and older participants, supporting the notion that the saccadic motor system is relatively unaffected by the aging process (Kadota & Gomi, 2010; Pratt et al., 2006; Yang & Kapoula, 2006). Finally, all main effects of AGE regarding eye–hand coordination were part of significant AGE  $\times$  PHYSICAL ACTIVITY LEVEL interactions, and consequently are discussed in Section 3.1.3.

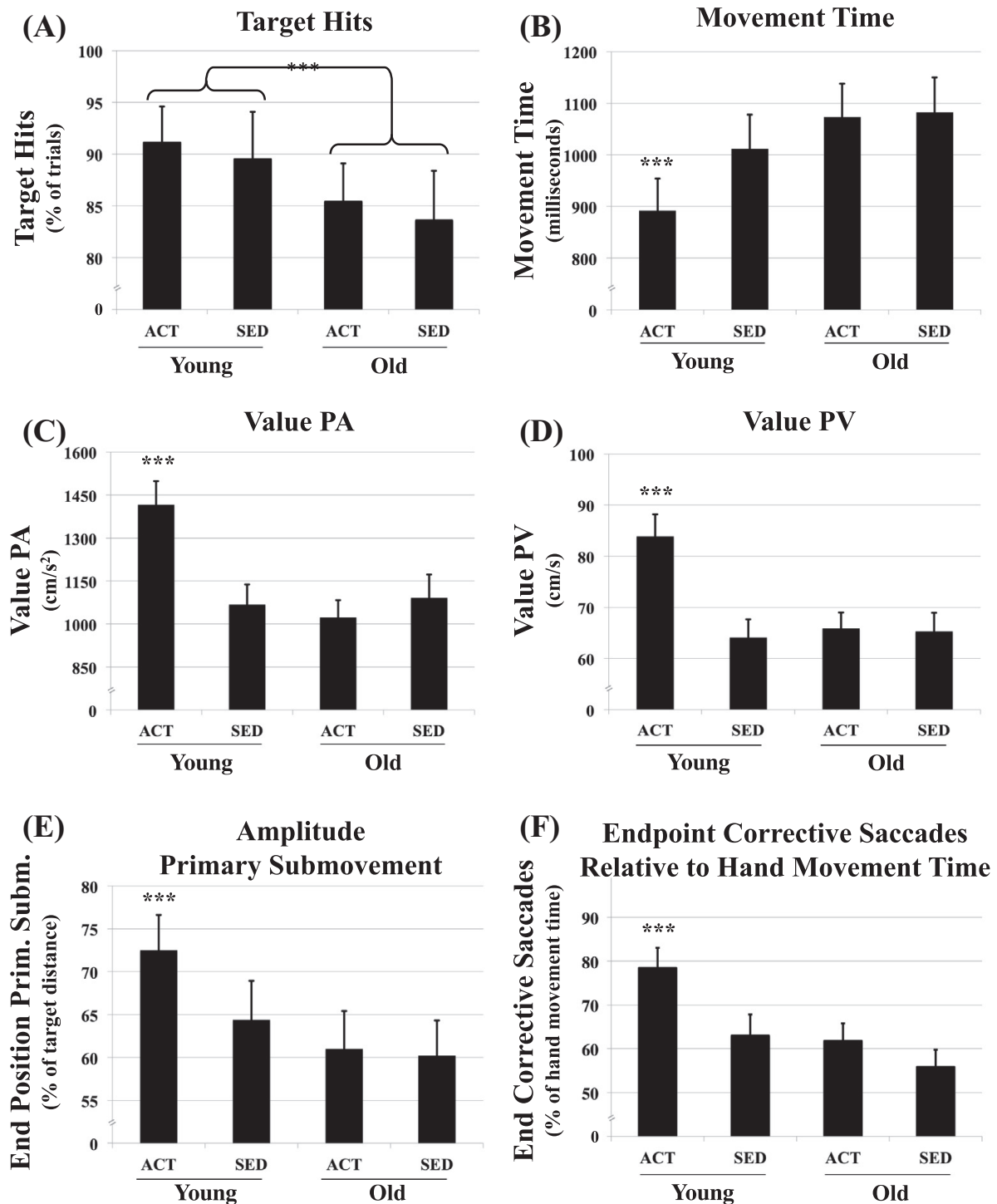
### 3.1.2. Impact of physical activity level

A brief glance at Table 2 reveals that the impact of physical activity level was less distinct than the impact of age. Only one main effect of PHYSICAL ACTIVITY LEVEL was not part of a significant AGE  $\times$  PHYSICAL ACTIVITY LEVEL interaction: Compared to their active counterparts, sedentary adults tended to position the cursor slightly more towards the right at the start of the aiming movement ( $p < .05$ ). However, as all groups still obeyed the instruction to surround the right target at the start of the movement, this effect was considered irrelevant. Again, all other significant effects are discussed in Section 3.1.3.

### 3.1.3. Interaction effects of age and physical activity level

A closer look into the AGE  $\times$  PHYSICAL ACTIVITY LEVEL interactions revealed that particularly active young participants differed from the others. Post-hoc tests indicated they demonstrated shorter hand movement times ( $p < .01$ ; see Fig. 3B), more forceful and faster initial impulses (both  $p < .01$ ; PA and PV values depicted in Fig. 3C and D, respectively) resulting in relatively longer-ranged primary submovements ( $p < .01$ ; see Fig. 3E), whereas no significant differences were found between any other groups. The high resemblance between the aiming movements of active and sedentary older adults does not support the hypothesis that a physically active lifestyle can attenuate the typical age-related movement adaptations in discrete manual aiming. This finding therefore seems inconsistent with previous research showing better performances in physically active older adults (Van Halewyck et al., *in press*). Nevertheless, the different aiming paradigms used in the two studies could potentially explain this inconsistency: the current experiment examined discrete aiming movements, whereas the previous experiment focused on cyclical aiming. According to Teeken and colleagues (1996), such a paradigm shift may cause age effects to be expressed differently. The same may account for the mediating effect of physical activity. Furthermore, the overall distribution in Baecke scores among the older adults was slightly smaller in the current study compared to the previous one. This too could explain why the differences between active and sedentary older adults emerged to a lesser extent in this experiment.

In general, active young adults distinguished themselves from the other groups with respect to eye movements and eye–hand coordination as well. For instance, post hoc tests revealed the primary saccade latency of active young adults was shorter compared to their older and sedentary counterparts ( $p < .01$ ). On the other hand, sedentary young adults spent slightly less time on their primary saccades compared to their active and older counterparts ( $p < .001$ ), which makes sense as their initial saccade tended to undershoot the target to a greater extent. Post-hoc tests concerning the amplitude of the primary and corrective saccades failed to reach significance nonetheless ( $p > .10$ ). Regarding eye–hand coordination, sedentary young adults started their primary saccade relatively later during the hand movement compared to both older adult groups (both  $p < .01$ ). The notion that the hand started moving first may seem remarkable as primary saccades generally precede the hand movement (Helsen et al., 1998). Since this outcome was observed consistently among groups, however, it may be due to our specific instructions. As indicated in the *Task and Protocol* section, we repeatedly instructed participants to fixate the starting target during practice blocks in order to prevent anticipatory saccades.



**Fig. 3.** Research question 1: What is the impact of age and physical activity level on eye–hand coordination during discrete manual aiming? Overview of group scores (mean  $\pm$  SEM) on a selection of variables in the VISION condition. *Note:* Due to a lack of a significant interaction in the percentage of target hits, a main effect of age is displayed in (A), whereas significant interactions between age and physical activity level are depicted on all other graphs ([B]–[F]). Significant differences are highlighted by \* (if  $p < .05$ ) or \*\*\* (if  $p < .01$ ).

Perhaps this instruction was repeated one too many times, thereby overemphasizing the initial fixation and unintentionally prolonging the eye-movement latency. Yet, more important is the saccadic behavior later in the movement when visual feedback is processed to reduce the spatial discrepancy between the cursor position and the end target. In this respect, active young adults started and ended

their corrective saccades relatively later in the hand movement time than the other three groups ( $p < .01$ ; end of corrective saccades displayed in Fig. 3F). Considering their shorter hand movement times, the latter clearly shows that active young adults used the least amount of time to make hand corrections after the gaze had reached its final position. In absolute numbers, active young adults needed less than 200 ms on average to eliminate the spatial discrepancy between the cursor and target based on their final fixation, whereas this time period covered at least 375 ms in the other groups.

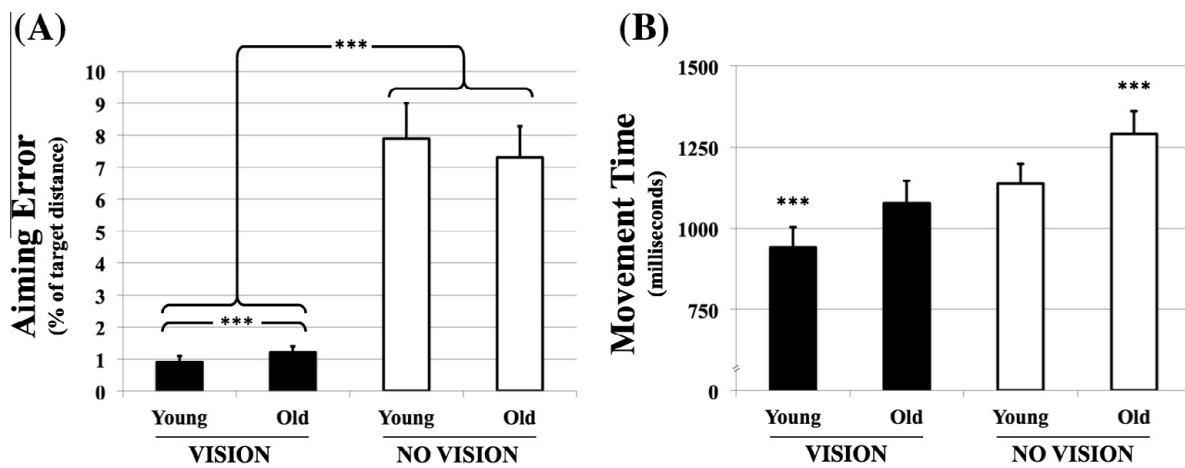
These outcomes seem consistent with the theory of an increased reliance on visual feedback during aiming in old age, and even imply it may be extended to a sedentary lifestyle as well. However, if this were the case, the aiming performance of older and sedentary young participants should be affected more by the withdrawal of vision. If withdrawing vision does *not* disturb older and sedentary young adults' aiming movement to a greater extent, other factors might be in play. Before further interpreting the results concerning eye–hand coordination, we therefore first shed some light on the importance of visual feedback on manual aiming performance.

### 3.2. Research question 2: Are older adults more reliant on visual feedback during discrete manual aiming?

For the sake of completeness, Table 3 summarizes all results of the NO VISION condition in a similar fashion as Table 2 does for the VISION condition. Finally, a comparison between both visual conditions is provided in Table 4. With respect to the current study's goal, we have limited our discussion to the results considered relevant to our research question.

As expected, withdrawing visual feedback had a clear impact on endpoint accuracy in general: The overall percentage of target hits dropped by more than 60% and the mean aiming error increased over sevenfold (both  $p < .0001$ ). Interestingly, the removal of vision did not impact young and older adults' distribution of target undershoots, hits or overshoots differently (both  $p > .05$ ; see Table 4). This seems to imply that older adults are not more reliant on visual information during manual aiming<sup>1</sup>. In fact, just as in Chaput and Proteau's original study (1996b), the removal of visual feedback increased the aiming error significantly more in the young ( $p < .05$ ), suggesting *they* rather than older adults were more reliant on vision. Though the NO VISION condition did not generate any age-related aiming error differences ( $p > .05$ ; see Table 3 and Fig. 4A) and this effect was mainly caused by young participants achieving lower aiming errors in the VISION condition, it still signals a greater advantage of vision in young adults. As stated by Seidler-Dobrin and Stelmach (1998), the young may enjoy more efficient visual feedback processing, clarifying why they perform better when vision is available but are not disadvantaged when it is removed. Still, this outcome seems to contradict the findings of both Chaput and Proteau's follow-up study (1996a) and Coats and Wann's more recent work (2011), both claiming the elimination of vision affected their older participants to a greater extent. Nonetheless, there seems to be an important difference between the current investigation and the two others: our older participants exhibited longer movement times than the young adults in the NO VISION condition ( $p < .005$ ; see Fig. 4B, white bars), whereas movement times were equal between young and older adults in both other studies. Without vision, participants can only rely on proprioceptive feedback to minimize the spatial discrepancy between the cursor and target. As stated earlier, proprioceptive acuity is known to deteriorate with age in challenging conditions (Boisgontier et al., 2012). By taking more time than young adults,

<sup>1</sup> To investigate age-related differences in the reliance on limb-target control in general, an additional *coefficient of determination* ( $R^2$ ) analysis was performed (Heath, 2005; Khan et al., 2006; Messier & Kalaska, 1999). In short, this regression technique allows to assess the proportion of movement endpoint variability that can be explained by the limb position at different kinematic markers. The rationale behind this technique is the following: If aiming movements are purely based on planning processes, one should be able to accurately predict the movement endpoint based on (early) kinematic marker positions, as no limb-target control occurs late in the movement. On the other hand, if aiming movements are strongly modified based on limb-target control, movement endpoints are more difficult to predict from (early) kinematic marker positions. Results of the VISION condition showed that less than 2% of the movement endpoint variance could be explained by the positions of the different kinematic markers (all  $R^2 < .02$ ). In the NO VISION condition, this proportion did not exceed 6% for any kinematic marker (all  $R^2 < .06$ ). These results imply that both age groups strongly relied on limb-target control, even when visual feedback was withdrawn. Finally, as no age-related  $R^2$  differences were observed in either condition, this additional analysis confirms the outcome that older adults are not more dependent on limb-target control.



**Fig. 4.** Research question 2: Are older adults more reliant on visual feedback during discrete manual aiming? Overview of the impact of the visual conditions on the aiming error (A), and the movement time (B) in both young and older adults. Group scores are presented as mean  $\pm$  SEM. Significant differences are highlighted by \* (if  $p < .05$ ) or \*\*\* (if  $p < .01$ ).

older adults may have reduced the imposed time-pressure deliberately, thereby making the aiming movements less challenging and possibly countering the age-related decline in proprioception (Boisgontier & Nougier, 2013). This suggestion is additionally supported by the finding that only the older participants increased their number of hand trajectory corrections when vision was withdrawn ( $p < .05$ ; see Table 4; Seidler-Dobrin & Stelmach, 1998).

Finally, it should be noted that active and sedentary adults were also similarly affected by the withdrawal of vision, as no significant PHYSICAL ACTIVITY LEVEL  $\times$  VISUAL CONDITION interactions regarding accuracy parameters were observed (all  $p > .10$ ; see Table 4).

### 3.3. General discussion

The focus of the current study was twofold. In short, the first analysis determined the impact of age and physical activity level on hand- and eye-movement kinematics and coordination during discrete manual aiming (VISION condition, see Table 2). Secondly, by withdrawing visual feedback (NO VISION condition, see Table 3) and comparing these results with the VISION condition (see Table 4), we investigated whether older adults were more reliant on visual information during the execution of discrete aiming tasks.

Results of the first analysis are largely in line with the available literature on aiming and aging. Older adults produced slower and less forceful primary submovements that undershot the target to a greater extent. This resulted in longer homing-in phases, and consequently greater movement times. Yet, there are also several new findings that extend the limited knowledge base on the impact of physical activity level on manual aiming and the temporal coupling between eye and hand movements in old age. Despite the fact that the division of active and sedentary young adults was only based on a generic level (Baecke questionnaire), clear movement differences emerged between groups. Specifically, active young adults made efficient primary submovements characterized by a forceful yet controlled impulse over a long range, whereas the primary submovements of sedentary young adults strongly resembled those of older adults. Besides this effect of physical activity level in young adults, one of the most remarkable outcomes of the first analysis is undoubtedly the finding that older and sedentary young adults spend a greater amount of hand movement time after the final fixation of the eyes. At first glance, this seems to suggest they tend towards an increased reliance on limb-target control in general – and late visual feedback in particular. If this were the case, however, one could expect more detrimental effects of removing vision in older and sedentary young adults. The second and third analyses nevertheless showed that the aiming accuracy of older (and sedentary young) adults was *not* affected to a greater extent when vision of the cursor was withdrawn. When considering all three



analyses, movement alterations in older and sedentary young adults such as slowing down the primary submovement and spending more time homing-in on the target may thus be caused by other factors than an augmented reliance on limb-target control. We suggest three possibilities.

First, spending a greater proportion of time in the homing-in phase of the movement may represent a *decreased efficiency in the processing of online feedback*. Though the literature lacks a direct comparison of physically active and sedentary young adults, many researchers have already acknowledged a decreased processing speed could be a key factor in explaining age-related motor slowing (Chaput & Proteau, 1996a; Rand & Stelmach, 2012; Temprado et al., 2013). More specifically, increased levels of neural noise have been hypothesized to underlie motor slowing by perturbing the signal transmission of the central nervous system (Rey-Robert et al., 2012). Regarding the specific sources of feedback, Chaput and Proteau (1996a) stated that aging may be associated with a slower processing of visual information. In this context, the speed of afferent visual signals and intra-cortical visual processes are thought to be slowed down in older adults by a gradual loss of myelin (Porciatti et al., 1999). Furthermore, the previously described degeneration in proprioceptive acuity and position sense in challenging conditions (Boisgontier et al., 2012; Wright et al., 2011) may additionally impede accurate feedback processing in older adults (Rand & Stelmach, 2012).

Second, the observed movement alterations may also be a direct consequence of *deteriorated motor planning capacities* in older and sedentary young adults. This hypothesis is based on previous studies reporting increased spatial and temporal variability in older adults' movement trajectories (Christou & Carlton, 2001; Ketcham et al., 2002; Pratt et al., 1994; Yan et al., 1998). In line with the results of Galganski, Fuglevand, and Enoka (1993), an age-related decline in the ability to tune muscular forces may result in an increased endpoint variability of the primary submovement when older adults move at similar speeds as young controls. Taking into account that the endpoint variability of primary submovements within participants relates in a linear fashion with movement velocity (Elliott et al., 2010), older adults may slow down their primary submovements in order to keep variability low and prevent the high energy-cost associated with a target overshoot. As a result, they undershoot the target on average to a greater extent, thereby increasing the distance to be traveled during the homing-in phase. Needless to say, traveling a larger distance in the final movement phase requires a prolonged time period spent homing-in on the target. A similar mechanism could explain our observations in sedentary adults as well, as they too demonstrated slower and shorter-ranged primary submovements, and spent more absolute time in the final movement stage than their active counterparts.

Finally, instead of a physical decline, considerably undershooting the target and consequently spending more time during the homing-in phase could also represent a *play-it-safe strategy* adopted by older adults. In many daily-life aiming and reaching situations, there are safety advantages associated with undershooting the target (e.g., when reaching for a pot of boiling water). According to Boisseau et al. (2002), older adults tend to be more cautious than young adults during motor behavior, which might explain why they usually undershoot the target to a greater extent (Elliott et al., 2010; Welsh et al., 2007). In this case, spending more time homing-in on the target would not necessarily indicate an augmented reliance on limb-target control, but rather arise from an increased prudence in older adults. From this point of view, one would nonetheless expect an aging effect on the amount of target overshoots, which was not found in the current study. Furthermore, the hypothesis does not explain why similar movement adaptations were detected in sedentary young adults, since there is no evidence they act more cautiously than their physically active counterparts.

To specifically determine which of these three factors is/are the underlying mechanism(s) for the observed movement alterations in older and sedentary young participants, future research should attempt to isolate these factors and investigate the specific effects of both age and physical activity. A final, general recommendation for studies on manual aiming and visual control of voluntary movement is to take into account participants' age and physical activity level, as both variables do seem to have a clear impact on eye–hand coordination.

## Conflict of interest

The authors declare that they have no conflict of interest.

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## References

- Baecke, J. A., Burema, J., & Frijters, J. E. (1982). A short questionnaire for the measurement of habitual physical activity in epidemiological studies. *The American Journal of Clinical Nutrition*, 36, 936–942.
- Boisgontier, M. P., & Nougier, V. (2013). Ageing of internal models: From a continuous to an intermittent proprioceptive control of movement. *Age*, 35, 1339–1355.
- Boisgontier, M. P., Olivier, I., Chenu, O., & Nougier, V. (2012). Presbyopia: The effects of physiological ageing on proprioceptive control. *Age*, 34, 1179–1194.
- Boisseau, E., Scherzer, P., & Cohen, H. (2002). Eye–hand coordination in aging and in Parkinson's disease. *Aging Neuropsychology and Cognition*, 9, 266–275.
- Chaput, S., & Proteau, L. (1996a). Aging and motor control. *The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences*, 51, 346–355.
- Chaput, S., & Proteau, L. (1996b). Modifications with aging in the role played by vision and proprioception for movement control. *Experimental Aging Research*, 22, 1–21.
- Christou, E. A., & Carlton, L. G. (2001). Old adults exhibit greater motor output variability than young adults only during rapid discrete isometric contractions. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, 56, 524–532.
- Coats, R. O., & Wann, J. P. (2011). The reliance on visual feedback control by older adults is highlighted in tasks requiring precise endpoint placement and precision grip. *Experimental Brain Research*, 214, 139–150.
- DiPietro, L. (2001). Physical activity in aging: Changes in patterns and their relationship to health and function. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, 56, 13–22.
- Elliott, D., Hansen, S., Grierson, L. E., Lyons, J., Bennett, S. J., & Hayes, S. J. (2010). Goal-directed aiming: Two components but multiple processes. *Psychological Bulletin*, 136, 1023–1044.
- Elliott, D., Hansen, S., Mendoza, J., & Tremblay, L. (2004). Learning to optimize speed, accuracy, and energy expenditure: A framework for understanding speed-accuracy relations in goal-directed aiming. *Journal of Motor Behavior*, 36, 339–351.
- Elliott, D., Helsen, W. F., & Chua, R. (2001). A century later: Woodworth's (1899) two-component model of goal-directed aiming. *Psychological Bulletin*, 127, 342–357.
- Engelbrecht, S. E., Berthier, N. E., & O'Sullivan, L. P. (2003). The undershoot bias: Learning to act optimally under uncertainty. *Psychological Science*, 14, 257–261.
- Galganski, M. E., Fuglevand, A. J., & Enoka, R. M. (1993). Reduced control of motor output in a human hand muscle of elderly subjects during submaximal contractions. *Journal of Neurophysiology*, 69, 2108–2115.
- Heath, M. (2005). Role of limb and target vision in the online control of memory-guided reaches. *Motor Control*, 9, 281–311.
- Helsen, W. F., Elliott, D., Starkes, J. L., & Ricker, K. L. (1998). Temporal and spatial coupling of point of gaze and hand movements in aiming. *Journal of Motor Behavior*, 30, 249–259.
- Kadota, K., & Gomi, H. (2010). Implicit visuomotor processing for quick online reactions is robust against aging. *The Journal of Neuroscience*, 30, 205–209.
- Ketcham, C. J., Seidler, R. D., Van Gemmert, A. W., & Stelmach, G. E. (2002). Age-related kinematic differences as influenced by task difficulty, target size, and movement amplitude. *The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences*, 57, 54–64.
- Khan, M. A., & Franks, I. M. (2000). The effect of practice on component submovements is dependent on the availability of visual feedback. *Journal of Motor Behavior*, 32, 227–240.
- Khan, M. A., Franks, I. M., Elliott, D., Lawrence, G. P., Chua, R., Bernier, P. M., et al (2006). Inferring online and offline processing of visual feedback in target-directed movements from kinematic data. *Neuroscience and Biobehavioral Reviews*, 30, 1106–1121.
- Khan, M. A., Franks, I. M., & Goodman, D. (1998). The effect of practice on the control of rapid aiming movements: Evidence for an interdependency between programming and feedback processing. *The Quarterly Journal of Experimental Psychology*, 51, 425–444.
- Lavrysen, A., Elliott, D., Buekers, M. J., Feys, P., & Helsen, W. F. (2007). Eye–hand coordination asymmetries in manual aiming. *Journal of Motor Behavior*, 39, 9–18.
- Lavrysen, A., Heremans, E., Peeters, R., Wenderoth, N., Feys, P., Swinnen, S. P., et al (2012). Hemispheric asymmetries in goal-directed hand movements are independent of hand preference. *NeuroImage*, 62, 1815–1824.
- Lavrysen, A., Heremans, E., Peeters, R., Wenderoth, N., Helsen, W. F., Feys, P., et al (2008). Hemispheric asymmetries in eye–hand coordination. *NeuroImage*, 39, 1938–1949.
- Lyons, J., Elliott, D., Swanson, L. R., & Chua, R. (1996). Use of vision in manual aiming by young and older adults. *Journal of Aging and Physical Activity*, 4, 165–178.
- Mathiowetz, V., Volland, G., Kashman, N., & Weber, K. (1985). Adult norms for the Box and Block Test of manual dexterity. *The American Journal of Occupational Therapy*, 39, 386–391.
- Messier, J., & Kalaska, J. F. (1999). Comparison of variability of initial kinematics and endpoints of reaching movements. *Experimental Brain Research*, 125, 139–152.
- Meyer, D. E., Abrams, R. A., Kornblum, S., Wright, C. E., & Smith, J. E. (1988). Optimality in human motor performance: Ideal control of rapid aimed movements. *Psychological Review*, 95, 340–370.
- Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, 9, 97–113.
- Oxford Grice, K., Vogel, K. A., Le, V., Mitchell, A., Muniz, S., & Vollmer, M. A. (2003). Adult norms for a commercially available Nine Hole Peg Test for finger dexterity. *The American Journal of Occupational Therapy*, 57, 570–573.

- Porciatti, V., Fiorentini, A., Morrone, M. C., & Burr, D. C. (1999). The effects of ageing on reaction times to motion onset. *Vision Research*, 39, 2157–2164.
- Poston, B., Van Gemmert, A. W., Bardusson, B., & Stelmach, G. E. (2009). Movement structure in young and elderly adults during goal-directed movements of the left and right arm. *Brain and Cognition*, 69, 30–38.
- Pratt, J., Chasteen, A. L., & Abrams, R. A. (1994). Rapid aimed limb movements: Age differences and practice effects in component submovements. *Psychology and Aging*, 9, 325–334.
- Pratt, J., Dodd, M., & Welsh, T. (2006). Growing older does not always mean moving slower: Examining aging and the saccadic motor system. *Journal of Motor Behavior*, 38, 373–382.
- Rand, M. K., & Stelmach, G. E. (2011a). Adaptation of gaze anchoring through practice in young and older adults. *Neuroscience Letters*, 492, 47–51.
- Rand, M. K., & Stelmach, G. E. (2011b). Effects of hand termination and accuracy requirements on eye–hand coordination in older adults. *Behavioural Brain Research*, 219, 39–46.
- Rand, M. K., & Stelmach, G. E. (2012). Effect of aging on coordinated eye and hand movements with two-segment sequence. *Motor Control*, 16, 447–465.
- Rey-Robert, B., Temprado, J. J., Lemaire, P., & Berton, E. (2012). Combining movement kinematics, efficiency functions, and Brinley plots to study age-related slowing of sensorimotor processes: Insights from Fitts' task. *Gerontology*, 58, 171–180.
- Saunders, J. A., & Knill, D. C. (2003). Humans use continuous visual feedback from the hand to control fast reaching movements. *Experimental Brain Research*, 152, 341–352.
- Seidler-Dobrin, R. D., & Stelmach, G. E. (1998). Persistence in visual feedback control by the elderly. *Experimental Brain Research*, 119, 467–474.
- Teeken, J. C., Adam, J. J., Paas, F. G., van Boxtel, M. P., Houx, P. J., & Jolles, J. (1996). Effects of age and gender on discrete and reciprocal aiming movements. *Psychology and Aging*, 11, 195–198.
- Temprado, J. J., Sleimen-Malkoun, R., Lemaire, P., Rey-Robert, B., Retornaz, F., & Berton, E. (2013). Aging of sensorimotor processes: A systematic study in Fitts' task. *Experimental Brain Research*, 228, 105–116.
- Terrier, R., Forestier, N., Berrigan, F., Germain-Robitaille, M., Lavalliere, M., & Teasdale, N. (2011). Effect of terminal accuracy requirements on temporal gaze-hand coordination during fast discrete and reciprocal pointings. *Journal of Neuroengineering and Rehabilitation*, 8, 10.
- Van Halewyck, F., Lavrysen, A., Levin, O., Elliott, D., & Helsen, W.F. (in press). The impact of age and physical activity level on manual aiming performance. *Journal of Aging and Physical Activity*. Retrieved from [http://journals.humankinetics.com/AcuCustom/Sitename/Documents/DocumentItem/Van\\_Halewyck\\_japa\\_2013\\_0104-in\\_press.pdf](http://journals.humankinetics.com/AcuCustom/Sitename/Documents/DocumentItem/Van_Halewyck_japa_2013_0104-in_press.pdf).
- Voorrips, L. E., Ravelli, A. C., Dongelmans, P. C., Deurenberg, P., & Van Staveren, W. A. (1991). A physical activity questionnaire for the elderly. *Medicine and Science in Sports and Exercise*, 23, 974–979.
- Welsh, T. N., Higgins, L., & Elliott, D. (2007). Are there age-related differences in learning to optimize speed, accuracy, and energy expenditure? *Human Movement Science*, 26, 892–912.
- Woodworth, R. S. (1899). The accuracy of voluntary movement. *Psychological Review*, 3, 1–119.
- Wright, M. L., Adamo, D. E., & Brown, S. H. (2011). Age-related declines in the detection of passive wrist movement. *Neuroscience Letters*, 500, 108–112.
- Yan, J. H., Thomas, J. R., & Stelmach, G. E. (1998). Aging and rapid aiming arm movement control. *Experimental Aging Research*, 24, 155–168.
- Yang, Q., & Kapoula, Z. (2006). The control of vertical saccades in aged subjects. *Experimental Brain Research*, 171, 67–77.